Jet Cavitation Erosion of Hollow Cylinders*

(An Experimental Investigation into the Effects of Chamfers and Tapers)

Toshiharu KAZAMA **, Kento KUMAGAI ***, Ikuya SAKAMI **, Yukihito NARITA **

Erosion at the inner walls of hollow cylinders, in which cavitating jets flowed, was investigated experimentally using the jet cavitation erosion tester. Aluminum specimens with the representative size of 20 mm length, 20 mm outer diameter, and 5 mm inner diameter were prepared. The chamfered specimens had chamfers of 0.5, 1, 3, and 5 mm; the tapered specimens had tapers of 2.9°, 5.7°, 11.5°, and 17.2°. The test fluid was hydraulic oil with a viscosity grade of 32 and the oil temperature was maintained at 40°C. The upstream and downstream absolute pressures were 10.1 and 0.2 MPa. The standoff distance from the nozzle outlet and the specimen end surface was 15 mm. The exposure time was 8 hours and they were halved and observed after the experiment. The inner walls of the chamfered specimens were partially eroded at a slightly shorter distance from the chamfered edge of the downstream side, regardless of the chamfer magnitude. The erosion of divergent tapered specimens was not confirmed under the conditions.

Keywords: Cavitation, Erosion, Jet, Chamfer, Taper, Oil, Hydraulics, Geometry

1. Introduction

Cavitation erosion^{1),2)} in fluid machinery is predominantly caused by the collision of submerged cavitating jets and collapsing bubbles. Using a prototype based on the Lichtarowicz apparatus³⁾, many researchers have studied the erosion⁴⁾⁻⁸⁾ caused by cavitating jets^{9),10)}. However, in these studies, water was used as the test liquid and the jets were impinged vertically, and occasionally obliquely¹¹⁾, onto the specimen surfaces. There are few reports on erosion at the walls of the flow paths by cavitating jets with oils.

Erosion is also a serious problem in hydraulic equipment, such as hydraulic valves, positive displacement pumps, and motors. In certain situations, erosion occurs in the channels and passages in which the jets flow, especially in pressure, flow, and directional control valves, where the jets do not exactly impinge directly onto the surfaces of the inner walls. However, very few experiments have been performed to study the erosion at the walls along the flow paths by using cavitating oil jets.

In this study, we used hollow cylindrical specimens with chamfers and tapers and examined the effects of the geometry and flow on the location and magnitude of erosion.

The eroded parts of the specimens were observed, and the effects of experimental conditions on cavitation erosion were investigated.

2. Nomenclature

c	:	chamfer
D_i	:	specimen inner diameter
L	:	stand-off distance
p_d	:	downstream absolute pressure
p_u	:	upstream absolute pressure
t	:	exposure time
σ	:	cavitation number, $= p_d / p_u$
Subscript		
d	:	downstream
i	:	inner
u	:	upstream

3. Test Apparatus and Conditions

3.1 Test Apparatus

Figure 1 depicts the chamber, which is the main part of the test apparatus. The setup process, experimental conditions, and test procedures are discussed briefly here because the method used in this experiment is almost identical to that prescribed by the ASTM standards¹²⁾ and previously published papers^{13),14)}.

The hydraulic circuit consisted of the chamber, hydraulic power unit, hydraulic auxiliaries, and pressure and temperature sensors. The power unit had a positive displacement pump (maximum operating pressure of 40 MPa and discharge of 2.3×10^{-4} m³/s), electric motor, and reservoir. The accessories included valves, cooler, filter (nominal pore size of 3 μ m), and hoses. The sensors included pressure gages and a thermometer.

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** Muroran Institute of Technology
(27-1, Mizumoto-cho, Muroran, Hokkaido, Japan)
E-mail: kazama@mmm.muroran-it.ac.jp

*** Hitachi Construction Machinery Co., Ltd.
(650, Kandatsu, Tsuchiura, Ibaraki, Japan)

The chamber was made of stainless steel with two transparent windows on the sides. The inner diameter was 170 mm. The chamber included a long-orifice nozzle, holder to fix the nozzle, specimens (hollow cylinders), three struts and a mount to support the specimen, and spacers to adjust the location of the specimen. The nozzle had the flow path of 1 mm in diameter and 4 mm in length, and the flow path of the holder was 3 mm in diameter and 3 mm in length.

3.2 Test Conditions

The hollow cylindrical specimens¹⁵⁾ were prepared from an aluminum alloy (Japan Industrial Standards, JIS A5056). The outer diameter and length of the specimens were 20 mm and 20 mm, respectively. In this experiment, two types of specimens were prepared; chamfered and tapered. For chamfered specimens, the inner diameter was 5 mm and one end surface was chamfered at $c = 0.5, 1, 3,$ or 5 mm with a typical angle of 45° , while the other end was light-chamfered. For tapered specimens, the tapers were set at $2.9^\circ, 5.7^\circ, 11.5^\circ,$ and 17.2° , corresponding to the diameters of one end of the specimens to be 6, 7, 9, and, 11 mm and the other end to be 5 mm in all cases (designated as $\phi 5\text{--}\phi 6, \phi 5\text{--}\phi 7, \phi 5\text{--}\phi 9,$ and $\phi 5\text{--}\phi 11$ for divergent specimens, and $\phi 6\text{--}\phi 5, \phi 7\text{--}\phi 5, \phi 9\text{--}\phi 5,$ and $\phi 11\text{--}\phi 5$ for convergent specimens, respectively). By using these specimens, partial and whole, as well as divergent and convergent, flow paths were formed. The specimens were supported by three struts on the mount.

Because of the difficulties of machine processing, the hollows of the tapered specimens were manufactured by wire-cut electrical discharge machining, while the hollows of the chamfered specimens were bored by drilling. In addition, the eroded mass loss was infinitesimal, e.g., < 1 mg, up to $t = 8$ h under these experimental conditions. Thus, discussion of the aspects and the location of erosion can be meaningful, while a precise comparison of the eroded mass loss of specimens between the chamfered and tapered specimens may not be possible.

The stand-off distance L was defined as the distance between the edge-face of the nozzle outlet and the upstream-side end surface of the cylindrical specimens; the value of L was determined using annular spacers. The distance L was set to 15 mm, which was the condition for maximum erosion of a standard specimen without chamfer and taper.

The test liquid used was a mineral-oil-type hydraulic fluid of ISO viscosity grade VG 32 (kinematic viscosities of 32.6 mm²/s at 40°C and 5.49 mm²/s at 100°C). The oil temperature was maintained at $40 \pm 1^\circ\text{C}$ using an inline oil cooler. The test oil was recirculated and the air content was not controlled¹⁶⁾. The cavitation number σ is defined as the

ratio of the downstream absolute pressure p_d and the upstream pressure p_u . In the experiment, σ was set at 0.02 and p_u was maintained at 10.1 MPa

At the beginning of each test, the specimen was set, the chamber was filled with the test oil, and the remaining air and bubbles were carefully removed from the chamber. The submerged jet was cavitated through the nozzle and discharged into the chamber. The upstream and downstream pressures and the oil temperature were monitored continuously and controlled manually to maintain the prescribed experimental conditions during the test.

4. Results and Discussion

4.1 Chamfered Specimens

Figure 2 shows cross-sectional photographs of the specimens with chamfers $c = 0.5, 1, 3,$ and 5 mm. The specimens were cut using a precision machine tool after the completion of the experiments (accumulated exposure time $t = 8$ h). The conditions were as follows: main inner diameter $D_i = 5$ mm, cavitation number $\sigma = 0.02$, and stand-off distance $L = 15$ mm. The direction of the flow was right to left in these photographs, and the chamfered end surfaces of the specimens were placed at the downstream side. Erosion is visible in all specimens. The eroded region is indicated in the photographs by the rectangular in white, which was closed to the edge; but rather a slight distance from the end surface of the downstream side. As the chamfer became larger, the location moved to the upstream side. However, the distance from the outlet edge of the flow path, i.e., the circumferential line at intersection of the hollow path and the chamfer part, to the eroded region was nearly unchanged (approximately 1–2 mm). As a result, a chamfer at the downstream side did not impact the degree of erosion, and thus hardly contributed to reducing erosion.

Figure 3 shows photographs of the chamfered specimens where the direction of the flow was bottom up and the

Fig.1 Test chamber

chamfered end surfaces were placed at the upstream side. A similar degree of erosion was observed at the same location in all specimens. Therefore, a chamfer at the upstream side also did not influence the erosion.

In addition, we observed preliminarily the cavitating jets using a high-speed video camera and examined the processed images. However, the effects of chamfers on the flows were not markedly recognized at this stage.

4.2 Tapered Specimens

Figures 4 and 5 show the tapered specimens cut into halves after the experiment ($t = 8$ h). The flow direction is also bottom up. Photographs in Fig. 4 are the results of the divergent path and those in Fig. 5 are the results of the convergent path. Although it is difficult to convey with these pictures, the erosion pits were visible in the convergent path specimens, but not in the divergent specimens.

$c = 0.5$ mm

$c = 1$ mm

$c = 3$ mm

$c = 5$ mm

Fig.2 Photographs of specimens chamfered at the downstream side, halved after experiment

$c = 0.5$ mm

$c = 1$ mm

$c = 3$ mm

$c = 5$ mm

Fig.3 Photographs of specimens chamfered at the upstream side, halved after experiment

The end surfaces of the specimens were also carefully examined. However, erosion could not find almost all specimens. It should be noted here that minor defects (burrs) were observed at the outlet edge of the largely converged specimens, e.g., $D_i = \phi 11-\phi 5$.

Figures 6 and 7 are photographs of the end surfaces of the specimens after the experiment, corresponding to Figs. 4 and 5, respectively. The upper and lower pictures are the end

surfaces at the downstream and upstream sides, respectively. Erosion pits and damages were not visible in any of the specimens as shown in these photographs, except for the burrs mentioned above.

Figures 8 and 9 display the surface profiles close to the downstream end surface of the inner surfaces of the flow paths of the tapered specimens with the flow paths of the divergence ($\phi 5-\phi 11$) and convergence specimens ($\phi 11-\phi 5$).

Fig.4 Photographs of divergent tapered specimens, halved after experiment

Fig.5 Photographs of convergent tapered specimens, halved after experiment

The surface of the convergent specimen was eroded at 1–2 mm from the downstream edge, whereas the divergent specimen exhibited some roughness and a smooth surface.

5. Conclusions

This study examined the erosion of hollow cylinders by a cavitating jet. The effects of chamfers and tapers on the magnitude and location were examined experimentally to assess the erosion of oil-hydraulic valves. The salient

conclusions are as follows: For chamfered specimens, the inner walls were partially eroded at a slightly shorter distance from the chamfered edge of the downstream side. The aspect of erosion was not influenced by the chamfer magnitude. For tapered specimens, the inner walls of the straight and convergent tapered specimens were partially eroded close to the downstream surface end. In contrast, the divergent tapered specimens were not eroded under these experimental conditions.

$D_1 = \phi 5 - \phi 6$

$D_1 = \phi 5 - \phi 7$

$D_1 = \phi 5 - \phi 9$

$D_1 = \phi 5 - \phi 11$

Fig.6 Photographs of end surfaces of divergent tapered specimens
(upper: downstream side, lower: upstream side)

$D_1 = \phi 6 - \phi 5$

$D_1 = \phi 7 - \phi 5$

$D_1 = \phi 9 - \phi 5$

$D_1 = \phi 11 - \phi 5$

Fig.7 Photographs of the end surfaces of convergent tapered specimens
(upper: downstream side, lower: upstream side)

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Fig.8 Surface profiles of halved divergent specimens
($\phi 5-\phi 11$)

Fig.9 Surface profiles of halved convergent specimens
($\phi 11-\phi 5$)